The RAJA Encapsulation Model for Architecture Portability

DOE Centers of Excellence Performance Portability Meeting, Glendale AZ

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Overarching RAJA goal: enable portability with *small disruption* to application programming style

Balance Performance:

- Augment compiler's ability to optimize C++ code
  - Allow work-arounds when performance is not what's expected
- Simplify expression of various forms of fine-grained (on-node) parallelism

And Productivity:

- Single-source kernels
  - Do not bind an application to a particular PM technology
  - Best choice for a given platform or algorithm may not be clear
- Clear separation of responsibilities
  - **RAJA:** Encapsulate hardware and PM details and execute loops
  - **App:** Select iteration patterns and execution policies with RAJA API

Ideal: Developers add parallelism to code using RAJA encapsulation layer – preserve development dynamics and advantages of MPI heritage

RAJA is a low-risk way to realize latent fine-grain parallelism in existing applications

- Loop iteration and loop body are decoupled (body mostly unchanged, often untouched)
- A loop iteration is a "task" – reorder, schedule, aggregate, manage dependencies, etc.
- Explore implementation alternatives (tuning) without disrupting application source code

C-style for-loop

```
double* x ; double* y ;
double a, tsum = 0, tmin = MYMAX;
…
for ( int i = begin; i < end; ++i )  {
     y[i] += a * x[i] ;
     tsum += y[i] ;
     if ( y[i] < tmin ) tmin = y[i];
}
```

RAJA-style loop

```
double* x ; double* y ;
double a ;
RAJA::SumReduction<reduce_policy, double> tsum(0);
RAJA::MinReduction<reduce_policy, double> tmin(MYMAX);
…
RAJA::forall< exec_policy > ( IndexSet , [=] (int i) {
     y[i] += a * x[i] ;
     tsum += y[i];
     tmin.min( y[i] );
}  );
```

- RAJA encapsulation features
  - Traversals & execution policies (loop scheduling, execution, PM backends)
  - IndexSets (iteration space partition, ordering, dependencies, data placement, etc.)
  - Reduction types (programming model portability)

RAJA enables systematic architecture portability and tuning for large production codes

- Design based on loop / mesh traversal patterns in LLNL ASC codes
  - **A loop is the main conceptual abstraction in RAJA**
  - A typical LLNL multi-physics code has O(10K) loops, but O(10) loop *patterns*
  - App teams typically wrap RAJA in a “mini-DSL” that matches their style
- **RAJA can be used selectively and adopted incrementally**
  - Mapping loops to RAJA “execution policies” is key to performance
  - Important considerations: data motion, compute intensity, branch intensity, available parallelism, etc.
- Typical RAJA integration process:

1) Achieve basic portability
- Make code thread-safe where needed
- Convert loops to RAJA-style

Profile →

2) Tune exec policies
- Identify loop classes
- Map classes to architecture features using RAJA traversal templates and execution policies

Profile →

3) Explore tuning options
- Change iteration pattern (IndexSets)?
- Redesign algorithm or data layout?
- Code-specific RAJA constructs?

RAJA core abstractions can combined with application-specific implementations

Original app code

```
// Kernel 1
for (int i=begin; i<end; ++i) {
     Loop body 1 (stride-1)
}
 …
// Kernel 2
for (int i=0; i<len; ++i) {
     Loop body 2 (indirection)
}
…
// Kernel 3
…
// Kernel 4
…
```

Para-meterized RAJA loops

"RAJA-fied" app code

```
// Kernel 1 : "stream" → low FLOP/bandwidth
RAJA::forall<stream> ( begin, end, [=] (int i)  {
      Loop body 1
} );

// …
// Kernel 2 : "work" → high FLOP/bandwidth
RAJA::forall<work> ( iset, [=] (int i)  {
     Loop body 2 (iset = index "ranges" & "lists")
} );
```

Execution policies (app defined)

Arch A : `stream = seq, work = omp`

Arch B : `stream = omp, work = gpu`

Customized RAJA

```
// Kernel 3 : RAJA IndexSet w/ custom traversal
app::forall<app_policy> ( iset, [=] (…)  {
      Loop body 3
} );
```

Architecture-tailored implementations

Kernel 4 - Arch A

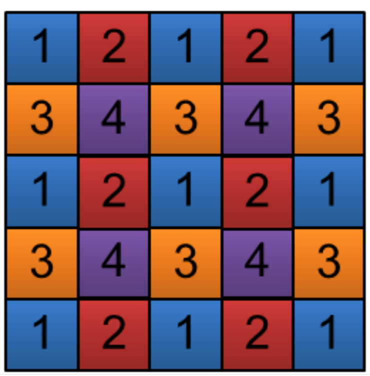
Kernel 4 - Arch B

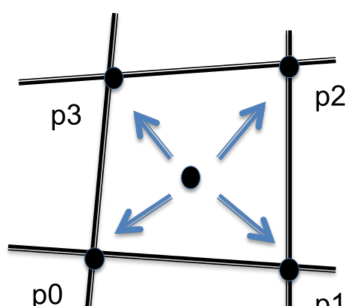
RAJA supports relatively simple parameterization of most loops.
Others may need customization or more severe disruption for desired performance.

RAJA IndexSets simplify thread-safe refactoring of code with data races

```
forall< colorset >(elemSet, [=] (int elem) {
   // Get element node ids
   int p0 = elemToNodeMap[elem][0];
   int p1 = elemToNodeMap[elem][1];
   int p2 = elemToNodeMap[elem][2];
   int p3 = elemToNodeMap[elem][3];

   // Accumulate volume to nodes
   double volFrac = elemVol[elem]/4.0 ;
   nodeVol[p0] += volFrac ;
   nodeVol[p1] += volFrac ;
   nodeVol[p2] += volFrac ;
   nodeVol[p3] += volFrac ;
} ) ;
```





- **Example code:** accumulate element volumes to mesh nodes
- Iterations are colored into sets of independent work (IndexSet Segments)
  - Iterate over segments sequentially
  - Execute each segment in parallel
- Without reordering, requires either:
  - Contention-heavy fine-grained sync ops (atomics / critical sections)
  - Temporary arrays for accumulating sums
- RAJA reordering allows use of coarse-grained synchronization
  - Less memory contention
  - Code remains as domain expert wrote it

RAJA IndexSets and traversals also enable developers to define & schedule dependencies

```
#pragma omp parallel for schedule(static,1)
for (int i = 0; i < is->num_seg; ++i) {
   IndexSetSegInfo* seg_info = iset.getSegmentInfo(i);
   DepGraphNode* task = seg_info->getDepGraphNode();
   while (task->semaphoreValue() != 0) {
      sched_yield() ;
   }

   execute<SEG_EXEC_POLICY>(seg_info, loop_body);

   if ( task->semaphoreReloadVaue() != 0 ) {
      task->semaphoreValue() = task->semaphoreReloadValue();
   }

   if ( task->numDepTasks() != 0 ) {
      for (int j = 0; j < task->numumDepTasks; ++j) {
         int seg = task->depTaskNum(j);
         DepGraphNode* dep = iset.getSegmentInfo(seg)->getDepGraphNode();
         __sync_fetch_and_sub(&(dep->semaphoreValue()), 1);

      }
   }
}
```

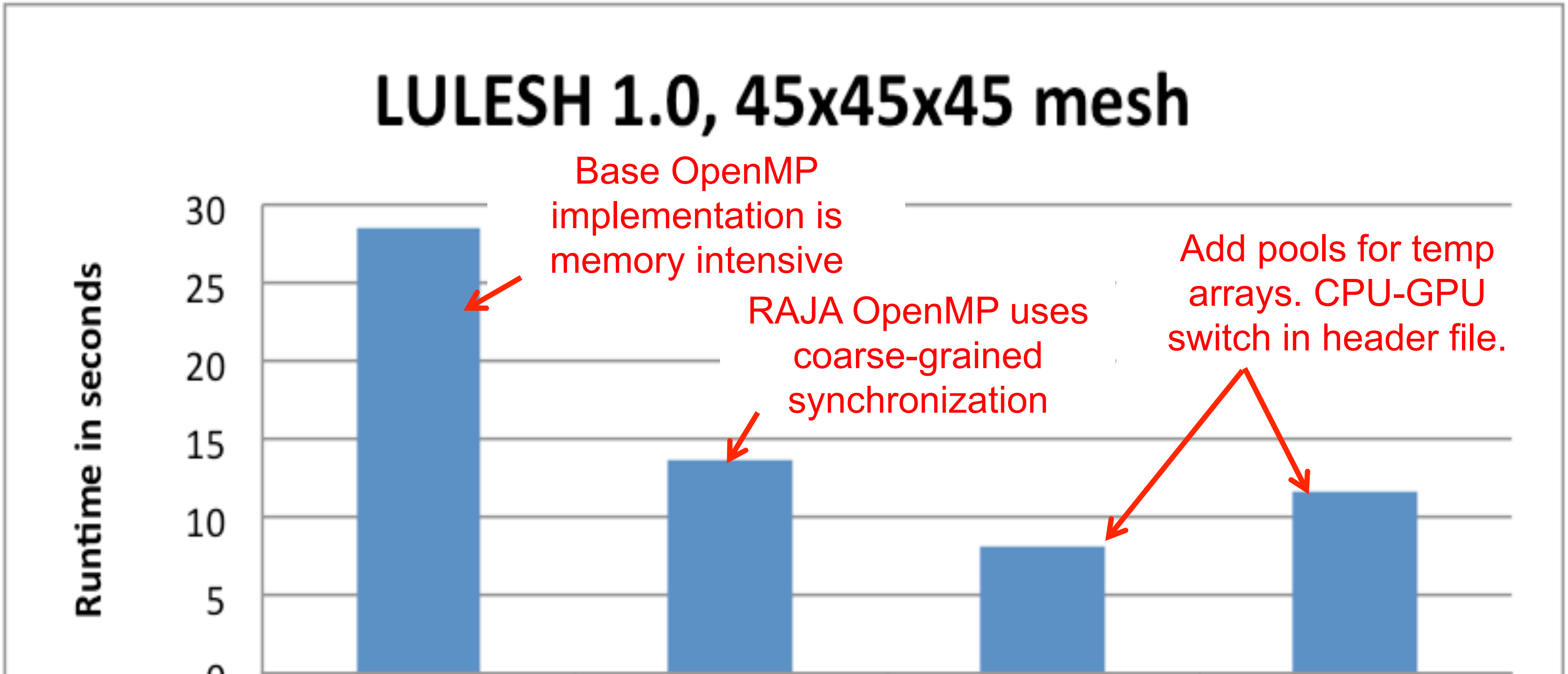
Wait for dependencies to be satisfied

Execute Segment

Reset dependency information

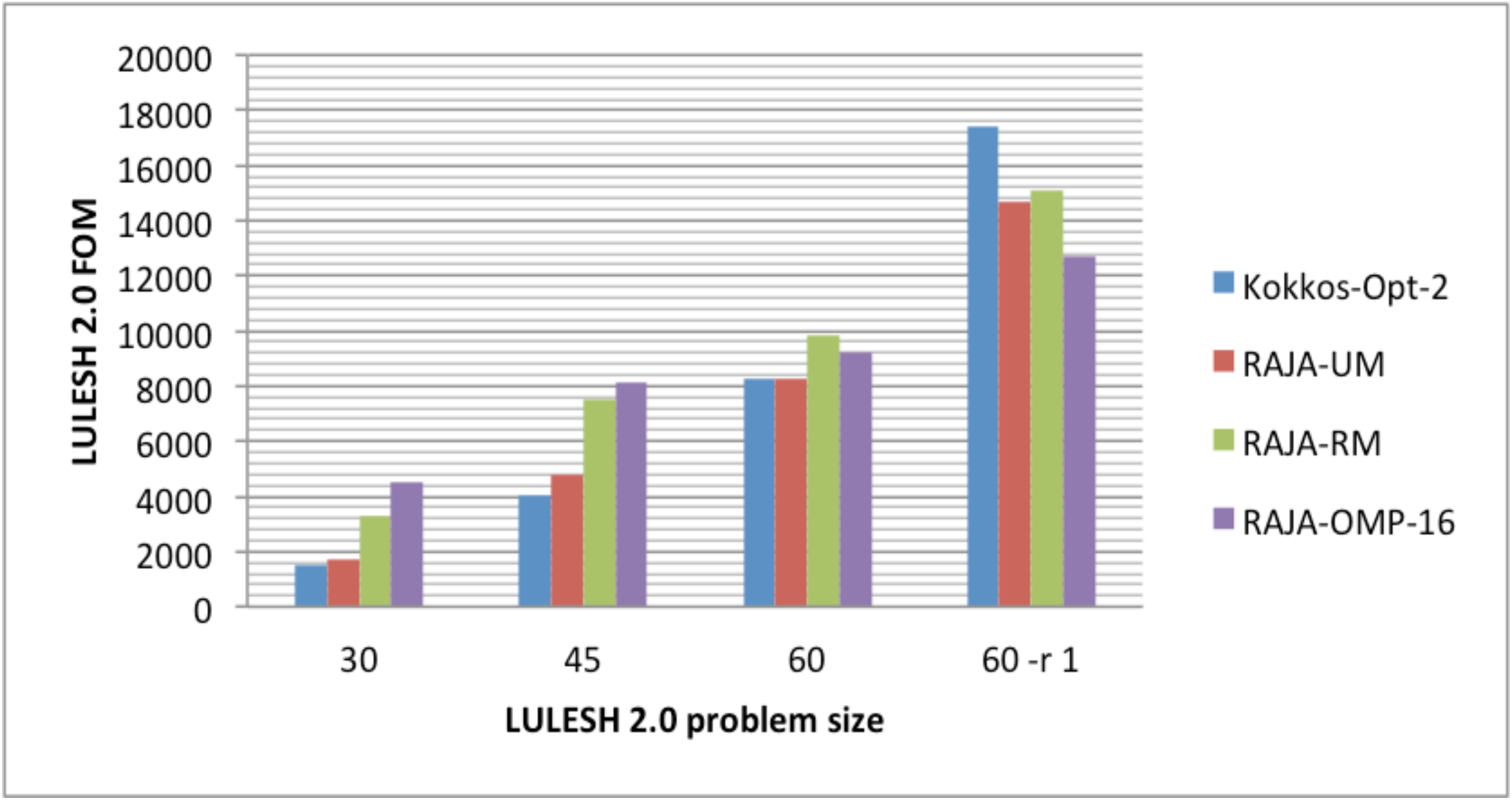
Segment scheduling control logic like this is hidden in a RAJA traversal template.

RAJA version of LULESH v1.0 hydro proxy app is an interesting case study



	Base-OMP-16	RAJA-OMP-16	RAJA-MEM-OMP-16	RAJA-MEM-GPU-HALF-K80
Series1	28.47	13.64	8.1	11.7

RAJA K80 GPU performance for LULESH v2.0 has improved markedly since FY15 ASC milestone



Compiled with nvcc 7.5 using compute_37

We are developing extensions and complements to RAJA that address other application needs

- Abstractions to automatically move data between DRAM and HBM or device memory – less code "clutter" than OpenMP 4 or CUDA:

ManagedArray objects know *what* data to copy

ResourceManager object knows *whether* to copy data

RAJA provides context to know *where* to copy data

David Poliakoff talk tomorrow

- forallN extensions for nested loops:
  - Supports loop interchange and data layout changes
  - Provides loop index types to ensure code is correct

Adam Kunen talk tomorrow

LLNL developers are assessing these concepts in production applications today.

RAJA enables a single source code base to run with multiple forms of parallelism

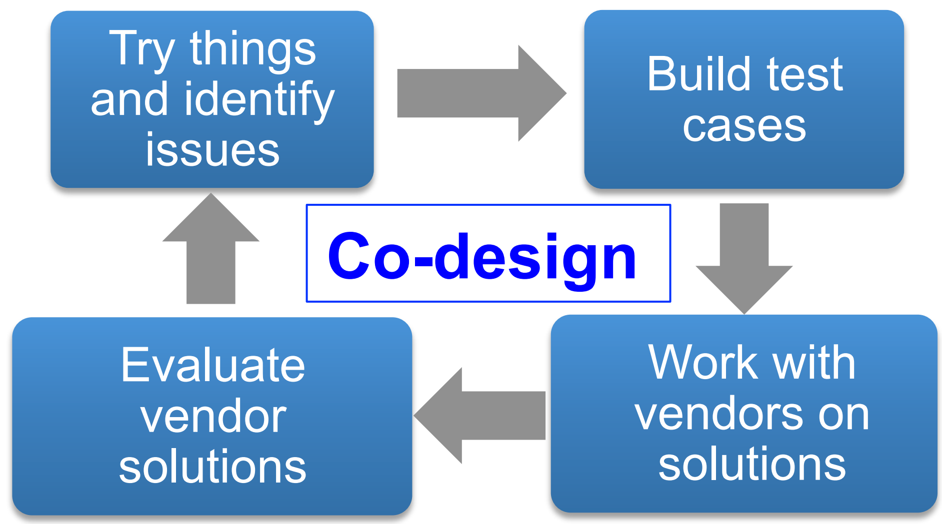
- CPU-GPU portability achieved with existing PMs and standard C++11
  - Often **does not** require much code restructuring (incl. reductions) or multiple versions
- RAJA can help make tuning more systematic
  - Focus on loop patterns, not individual loops
- IndexSets provide a lot of flexibility
  - Code specializations generated (and optimized) at compile-time. Execution paths through specializations selected at runtime.
  - Dependencies between iteration subsets (Segments) can be defined to ensure correctness
- Multiple LLNL projects contribute to RAJA: Ares, ALE3D, Ardra, AAPS, etc.
  - See David Beckingsale policy tuning talk tomorrow
- Three LLNL production apps are integrating RAJA to prepare for Trinity and Sierra : Ares, ALE3D, Ardra
- Other codes are exploring RAJA : NIF VBL, *hypre,* VisIt, hydra, MARBL
  - See Matt Martineau proxy-app talk tomorrow

An open-source RAJA release with example codes is imminent and will be available at http://github.com/LLNL/RAJA -- collaborators welcome!

Software engineering alone is not enough – we need to work closely with vendors too

- Compiler vendors & PM developers have been improving support for C++ based encapsulation
  - IBM, NVIDIA, Intel, GNU, AMD (Sierra CoE, DesignForward, FastForward, van trips…)
  - OpenMP 4.0 → OpenMP 4.5 & beyond (See Arpith Jacob talk next)
- Tool support for C++ templates : HPCToolkit, Intel

- We (DOE HPC community) must tell vendors what we need
- Good solutions involve negotiations (our needs, vendor priorities, language standards, vendor extensions, etc.)



A relatively small investment in compilers and runtimes (and vigilance) – compared to HW costs – can have a huge, positive, lasting impact on our codes. Issues we identify and work to resolve also benefit the broader HPC community.

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